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PhD Yearbook | 2022

Chiar:
Prof. Pierangelo Masarati

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

The aim of the course is the acquisition of the high level competences that are required to carry out innovative research and/or state of the art advanced applications in industries, public or private research centers, Universities or public and service companies in the area of aerospace engineering, including all the associated fields, with specific attention to its interaction with the human operators, the users, the environment and the society at large.
The level of the course provides the graduates with the ability to compete in a European and international environment.
The course duration is three years, requiring 180 credit points (ECTS), including possible study-abroad periods and internships in private or public institutions.
The program and credits are divided in two main educational areas:
1. Courses for at least 20 credits, on transferable competences (at least 10 credits), on themes specific of aerospace engineering disciplines (at least 5 credits), and the remainder on topics of choice, to be acquired during the first year;
2. Development of the Doctoral Thesis (160 credits): the thesis is developed within the Department or, in some cases, in other institutions, in close contact with the Department.
The research activity starts immediately (40 credits in the first year), and is developed in the second and third year (60 credits each) of the doctoral program.
If the candidate's background curriculum lacks some introductory knowledge required for the Doctorate, the Faculty Board will ask to recover such knowledge, with the assistance of the tutor.
Afterwards, the Faculty Board will verify the overcoming of whatever was lacking during the annual meeting of admission to the second year of the course.
The course program related to point 1 does not follow a rigid scheme. So, besides widening the basic scientific culture of the candidate, it takes into consideration also the objectives and the core topics of the candidate's thesis. The program will also consider general cultural requirements as well as what is deemed to be specifically related to the thesis subject, as agreed between the candidate and the Faculty Board.
For the completion of the research activity, a study period in a foreign country or in an external institution is allowed and strongly recommended. Its duration may range from a few weeks up to one and a half year, with an average duration of 6 months. The related activities are usually carried out in well known and qualified scientific institutions (universities, research centers, etc.), and contribute to the cultural and scientific achievements of the research.
Due to the amplitude and interdisciplinarity of the aerospace sector, the professional skills achievable will span a broad area and not cover just a specific topic.
The educational goals will create high level specialists in the domains of: helicopters and rotary wing aircraft, fixed wing aircraft, space vehicles and missions, and related technologies.

In this context, specific competence can be gained either in a single subject or in the integration of special subjects such as: Aerodynamics and Fluid Mechanics, Structures and Materials, Flight Mechanics and Control, and emerging disciplines requiring an enhanced multidisciplinary approach such as rotary wing aircraft, electric airplanes, drones, innovative materials and structures, space mission design, space trajectory design, space situation awareness, innovative propulsion technologies, advanced fluid dynamics, etc.
In this respect, some examples of professional skills achieved in the course of the past 35+ years of doctoral program are here reported:
- expert in computational and/or experimental fluid mechanics, with capabilities to develop methods and models for both aerospace applications and generic vehicles;
- expert in active and passive control of the dynamics of aerospace structures, integrating global and subsystem design;
- expert in active and passive structural safety of vehicles, both aerospace and non-aerospace;
- expert in vibration and noise control, including modeling analysis, system design and implementation of specific subsystems;
- expert in the dynamics and control of aerospace vehicles and related operational missions;
- expert in integrated design of complex aerospace systems, including their missions and overall life cycle.

Since its foundation, more than 35 years ago, the doctoral course in Aerospace Engineering awarded more than 150 PhDs.

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DYNAMICS, GUIDANCE AND CONTROL OF RECONFIGURABLE SPACECRAFT FORMATIONS IN MULTIBODY ENVIRONMENTS

Andrea Capannolo - Supervisor: Prof. Michèle Lavagna

Formation flying is increasingly becoming a hot topic in the context of future space missions, due to the intrinsic advantages in exploiting smaller distributed systems rather than a single, heavy platform. The virtual aperture of a distributed system provides larger baseline for several applications and measurements (such as telescopes or antennas), that cannot be achieved with a single physical structure. Furthermore, the separation of platforms and/or functions improves robustness to risks, as the failure of a single spacecraft does not imply the complete failure of the formation.
With the advent of space missions leveraging multibody gravitational environments (Earth-Moon, Sun-Earth, etc.), the concept of formation flying is being expanded to such scenarios. This enabled the development of new mission concepts, and the inheritance of the advantages provided by the more complex dynamics, such as the low acceleration regions around equilibrium points of binary systems.
The nature of distributed system, however, suffers from an increased need of control over the relative positions and distances between the spacecraft. This negatively reflects to all the aspects related to the spacecraft motion, from the orbit design to the guidance and maneuvering, with higher burden on the operations and the on-ground segment. The non-Keplerian, multibody environment further exacerbates such issues, with a more complex dynamics, and the lack of a parametric representation of the trajectories. In this context, the present work explores the several aspects that characterize non-Keplerian formations of satellites, from numerical approaches to orbits design, to the guidance and control of the distributed system, with the purpose of increasing the autonomy of the formation and reducing the efforts of the ground segment.
A first part of the work covers the topic of orbit design, proposing a simple and efficient computational scheme for trajectories generation in binary systems. The scheme is exploited to develop potential candidates for hosting a formation, in two different environments: a binary system with massive celestial bodies (Earth-Moon), and one with small irregular asteroids (65803 Didymos).

The selected trajectories are then studied in terms of formation design and autonomy. Quasi-periodic orbital structures are developed to enable a natural, bounded relative motion between the agents of the formation, minimizing the control effort and frequency for the maintenance.
Within such structures, transfers are computed and mapped to assess the cost effectiveness of on-orbit reconfigurations, and to provide a benchmark for on-board control schemes.

In terms of guidance and control, the present work develops light algorithms, suitable for on-board implementation, that minimize the on-ground computations. Through the usage of approximated quasi-periodic motion surfaces, simple parametrizations are introduced for a fast evaluation of target points to perform the reconfiguration maneuvers. By sequentially linearizing the dynamics, light optimal control schemes are implemented, namely a State Dependent Riccati Equation controller and a receding horizon Model Predictive Control. The two schemes are deeply analyzed and compared to highlight advantages and disadvantages of each, and to determine which is more suitable for the analyzed applications. Finally, adaptive laws are introduced for automatic tuning of the controllers' weights, to autonomously vary the control action despite the highly nonlinear dynamics, and without the need of dedicated optimizations for each transfer. The adaptive scheme confirmed to be a valuable approach, as it provided comparable results to a tailored tuning for each transfer, and in some cases, showed even lower transfer costs.

Overall, the combination of the proposed approaches for orbit design, guidance and control demonstrated to be an effective step towards the development of versatile formations in non-Keplerian environment, and to towards an increased autonomy of distributed systems.

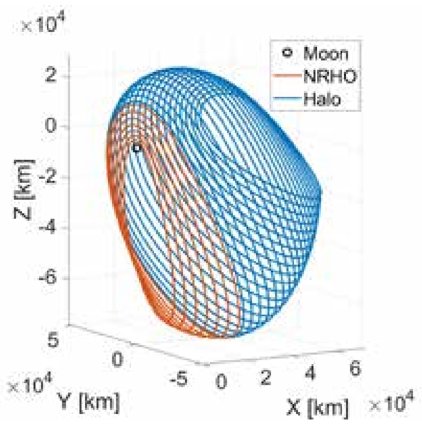

Fig. 1
Halo-NRHO family of the Earth-Moon system in the Circular Restricted Three Body Problem.

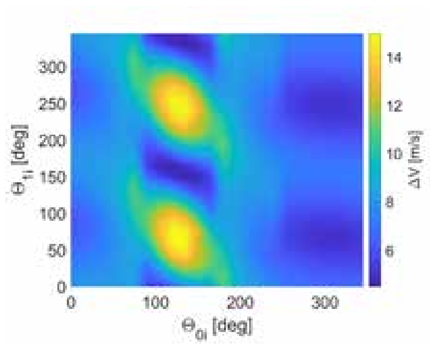

Fig. 2
Map of the optimal costs to reconfigure the follower spacecraft of a formation, given the position along the orbit and the phase with respect to the leader.

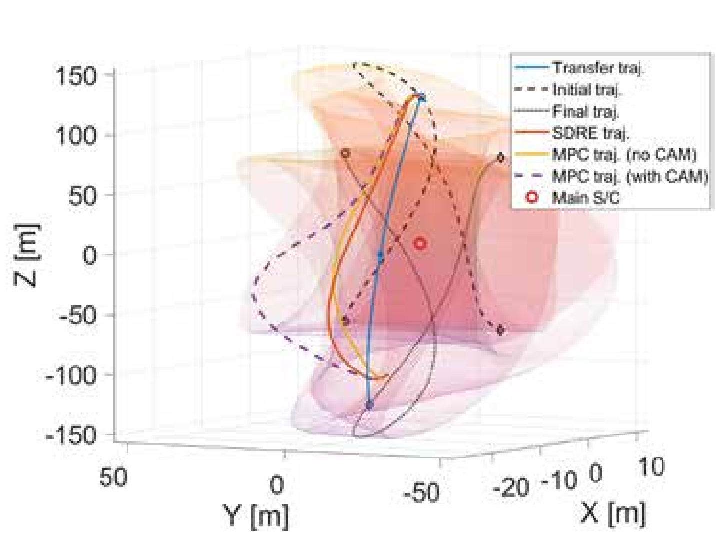

Fig. 3
Comparison between control schemes to reconfigure the follower spacecraft, leveraging the surface of quasi-periodic motion around the leader.

NON-IDEAL COMPRESSIBLE FLUID DYNAMICS OF ORGANIC VAPORS: FROM NOZZLE FLOWS TO PRESSURE PROBES

Camilla Cecilia Conti - Supervisors: Prof. Alberto Guardone - Prof. Vincenzo Dossena
Prof. Andrea Spinelli

Non-Ideal Compressible Fluid Dynamics (NICFD) is a branch of gasdynamics concerned with flows of dense vapors occurring close to the vapor-liquid equilibrium and the critical point, so in conditions in which the ideal gas law does not properly describe the thermodynamics involved. As a result and unlike an ideal gas, the flow field shows a marked dependance on process conditions. If molecularly complex fluids are considered, behaviours that are also qualitatively different with respect to an ideal gas are possible, such as the increase in speed of sound and non-monotone Mach number trends along isentropic expansions or a Mach number increase across oblique shocks.
Non-ideal flows occur in a wide range of engineering processes and the present work is specifically relevant for Organic Rankine Cycles (ORCs) in the power generation field. Fluids usually employed in ORCs feature high complexity and molecular weight, and turbine expansion occurs in the dense gas region near the saturation curve and the critical point. As a result, turbine flows are highly supersonic and show marked non-ideal flow effects.
Established studies on compressible flows are mostly based on the assumption of ideal gas behaviour. However, the latter model fails both quantitatively and qualitatively in describing non-ideal flows. Thus, a holistic approach involving theoretical, numerical and experimental aspects was carried out in the present work in order to contribute to the fundamental understanding of the relatively new field of NICFD.
Wind tunnel testing concerning non-ideal flows is intrinsically complex due to the high temperature and pressure conditions involved, as well as due to issues related to undesired vapor condensation. As a result, experimental data concerning such flows are scarcely available in literature for comparison with simulation and design tools. The large experimental data-set produced within this research includes subsonic and supersonic nozzle expansions and direct measures of normal shock losses, and contributes to filling the aforementioned literature gap. Moreover, the present work thus also contributes to establishing reliable methodologies for detailed nozzle flow characterization and pressure probes testing for non-ideal flows.
First of all, a theoretical calculation framework was implemented to investigate the non-ideal dependance of isentropic expansions on total conditions, with the aim of identifying similarity parameters that would provide further understanding of this peculiar behaviour and reduce the complexity of any problem in which non-ideal flows are encountered. Complex fluids in moderately high non-ideal conditions (representative of most engineering processes) were found to have similar expansions if total conditions share the same total compressibility factor ZT because they also share similar volumetric and caloric behaviour throughout the process. This was verified with extensive experimental campaigns on non-ideal supersonic nozzle flows on the Test Rig for Organic VApors (TROVA) at Politecnico di Milano, a blow-down wind tunnel specifically designed to reproduce non-ideal flows of organic vapours in conditions representative of ORC turbines operation. Tests were carried out covering a large portion of the vapor phase of fluid siloxane MM, commonly employed in high-temperature ORCs, from strongly non-ideal conditions with ZT = 0.39 to dilute ones at ZT = 0.98. Pressure measurements and Mach number extraction from schlieren visualizations, in synergy with numerical simulations, not only highlighted the non-ideal dependance of isentropic expansions on total conditions, but most importantly confirmed the suitability of the total compressibility factor as a similarity parameter for conditions with ZT > 0.60. Experimental testing on the TROVA was then performed to characterize moderately non-ideal expansions in choked subsonic nozzles at different Mach numbers. Pressure measurements, with the support of Laser Doppler Velocimetry (LDV) and numerical simulations, allowed to assess the impact of flow non-ideality in subsonic conditions and to verify that it is more marked where compressibility effects are also more relevant. Building on the knowledge of experimental testing and numerical simulation of elementary nozzle flows in the non-ideal regime, the focus was then shifted towards the development of experimental techniques for pressure probe testing in the TROVA. Several pneumatic lines configurations were assessed to overcome the most challenging experimental aspects, namely the transient nature of the TROVA operation and mass sink effects due to vapor condensation in the lines. A pneumatic scheme implementing nitrogen flushing was thus devised to allow pressure probes testing in subsonic and supersonic non-ideal flows.
An experimental campaign in the TROVA with Pitot tubes in non-ideal subsonic flows of organic vapors was then carried out to complete the pneumatic system commissioning and evaluate its performance for both total and static pressure measures against direct reference counterparts from the TROVA plant. Also, the campaign allowed to experimentally verify that flow non-ideality does not affect the behaviour of a Pitot tube in non-ideal subsonic flows, indicating that no particular calibration is required for this type of instrument in such compressible flow conditions.
Finally, Pitot tubes were employed to perform the first ever direct total pressure loss measurement across normal shock waves in non-ideal flows of siloxane MM vapors. This contributes to filling the current literature gap in available experimental results in NICFD and establishes a reliable methodology for such measurements, paving the way towards blade cascade testing in such flows and to pressure probes use in research and industrial contexts where non-ideality is relevant.

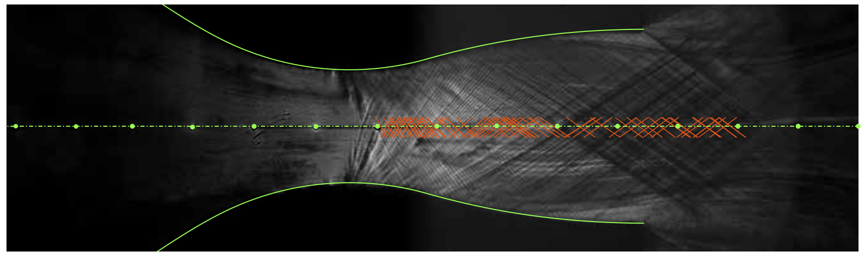

Fig. 1
Schlieren visualizations of supersonic non-ideal flows of siloxane MM vapor in the TROVA.

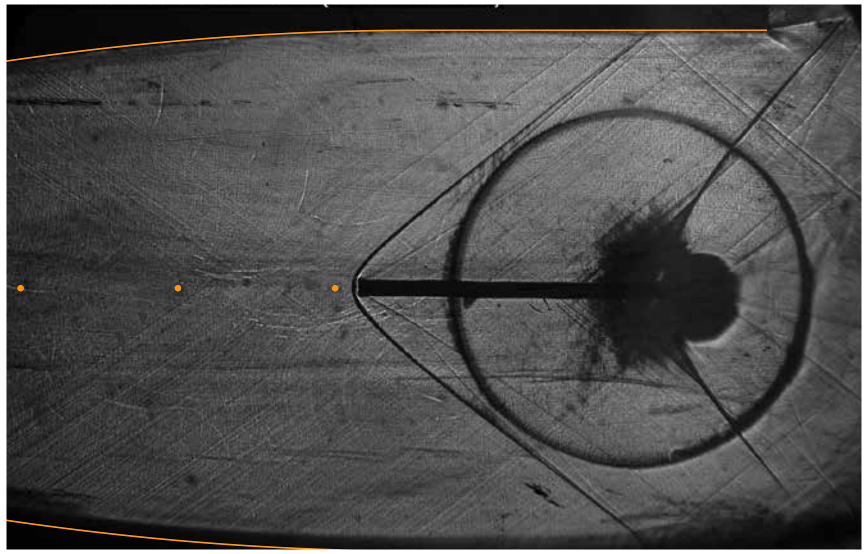

Fig. 2
Schlieren visualization of pressure probe testing in supersonic flows in the TROVA. A bow shock is evident at probe tip.

AUTONOMOUS NAVIGATION FOR INTERPLANETARY CUBESATS AT DIFFERENT SCALES

Vittorio Franzese - Prof. Francesco Topputo

Space exploration missions rely on ground-based orbit determination to properly locate and guide a spacecraft towards the mission target. This process involves ground tracking stations and flight dynamics teams to communicate with and control spacecraft in deep-space, and strongly contributes to the overall space mission costs. However, the recent proliferation of CubeSats is challenging the paradigm under which deep-space probes are navigated and controlled. Indeed, miniaturized spacecraft are increasing the overall number of spacecraft launches per year, thus yielding to a saturation of the ground-based tracking facilities. Moreover, the overall cost of deep space CubeSats scales down with the platform size with respect to traditional spacecraft, except for those related to navigation. This is because the same ground stations and teams are required to control spacecraft, regardless of the platform size. For these reasons, an increased level of autonomy onboard spacecraft is needed for deep-space CubeSats.

The PhD thesis "Autonomous Navigation for Interplanetary CubeSats at different scales" has investigated the feasibility of autonomous navigation methods for deep-space CubeSats at different range scale with respect to the mission target. To this aim, three navigation scenarios have been introduced and faced throughout the thesis, which are deep-space, far-range, and close-range with respect to the target, respectively. The navigation problem, solution, and performances for these scenarios have been presented and eventually simulated in real space mission studies, which are M-ARGO for the deep-space line-of-sight navigation scenario, LUMIO for the full-disk navigation in the far-range case, and MILANI for the centroiding at close-range to the target. Autonomous optical navigation in deep-space has the aim of estimating a spacecraft state through the triangulation of the line-of-sight directions to several visible targets, which are only seen as light dots in the image detected through centroiding methods. The visibility of these navigation beacons is dictated by the relative geometry between the observer and the targets in terms of distances, phase angles, and sun angles. These quantities affect the objects apparent magnitude as seen from an observer camera. The case of the M-ARGO CubeSat to rendezvous with five asteroids has been selected as study case. In this view, an optimal beacons selection criteria to select the best beacons from the position accuracy point of view has been derived. A study on how to increase the detectability range of the target asteroids has been performed. Then, the M-ARGO state in terms of

position and velocity covariance bounds has been estimated exploiting a navigation filter which is fed by the line-of-sight directions to the navigation beacons.

At far range with respect to the target, the spacecraft state can be estimated by acquiring and processing the apparent object contour, in case of a well-known nearly spherical object.
In the case of LUMIO, edge detection methods have been exploited to detect the Moon full disk, which is used to estimate the observer position via a family of centroid and diameter methods. An extended Kalman filter has been set in the LUMIO mission scenario to estimate the LUMIO state on the Halo orbit.
When in proximity to a target, such at close range to an asteroid, the detailed object view can be exploited to acquire the centroid of the object, and thus the relative line-of-sight direction between the observer and the target. This information is used in relative optical navigation scenarios as investigated for the MILANI mission. The spacecraft position is thus determined with respect to the visible asteroid in the camera field-of-view.

In conclusion, autonomous navigation for deep-space CubeSats is feasible. According to the observation scale, the environment can be acquired and processed to estimate the spacecraft position. In deep space, the far distant planets can be used to triangulate the spacecraft position, in far range with respect to a spherical object (e.g., the Moon), the object full disk can be used to estimate the relative distance between observer and target, while in close range with respect to an asteroid, the apparent shape and size of the body can be used to determine the CubeSat point of view.

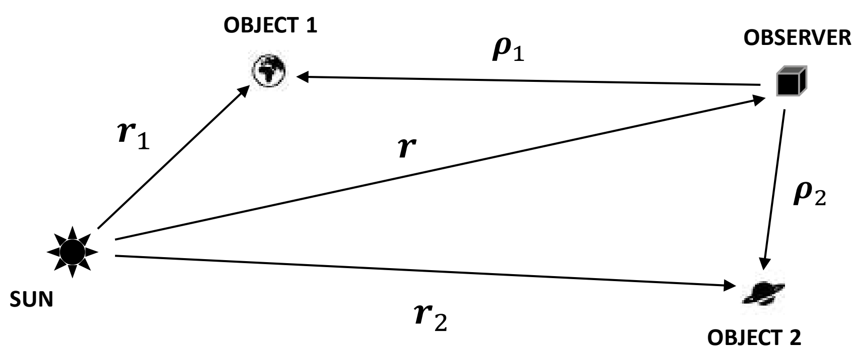

Fig. 1
Autonomous Navigation Geometry in Deep Space.

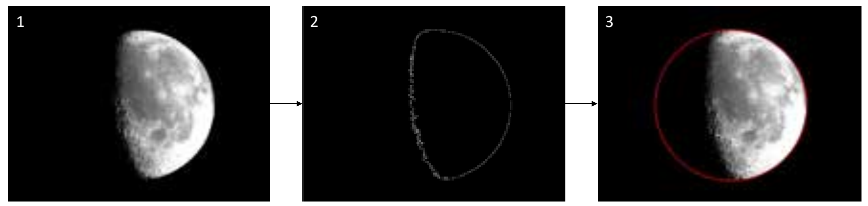

Fig. 2
Moon image processing to detect apparent disk.

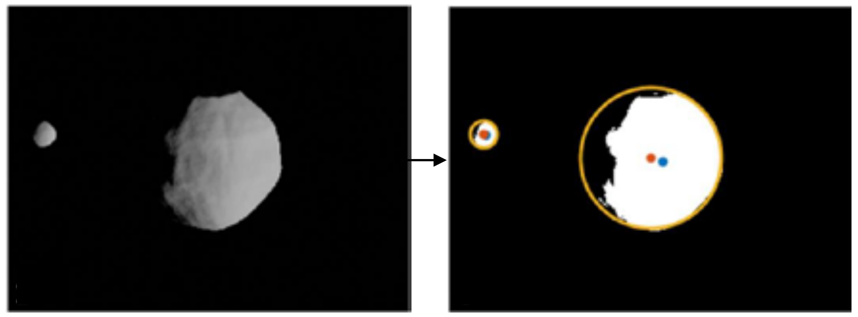

Fig. 3
Asteroid image processing for navigation.

MODELING AND MONITORING OF INTERFACE DAMAGE IN COMPOSITE IN THE PRESENCE OF RESIDUAL AND COMBINED STRESS STATES

Sara Ghiasvand - Supervisor: Prof. Alessandro Airoldi

Fiber/resin composites are advanced materials with a low weight to strength ratio, dimensional stability, custom design, corrosion resistance, durability, and flexibility that can substitute conventional materials in many fields. Moreover, due to their layered nature, composites can be combined with other materials, as in hybrid metallic/composite components, to fulfill diverse requirements like low working temperature or their properties in three-dimensional stress states as in hybrid structures. These irresistible features have made composites a preferred material choice among different materials by structural designers in the last decades.
Besides all the advantages of using advanced composite material, some aspects still limit the designer to use the maximum potential of this material. One of the most critical parameters in composite material is the detection of defects and damages, and quantification of their effect on the structure's strength. Composite-based structures are prone to many different modes of damage just in the composite phase, in addition to debonding that could occur in joints or adhesive interfaces. Most of these damages are not catastrophic per se but could degrade a high percentage of the structural strength and ultimately lead to final failure. Another important aspect of composites is their built-in residual thermal stress that arises during manufacturing due to their anisotropy Coefficient of Thermal Expansion (CTE), which can cause damage or distortion.
The typical way to increase the structure's safety is based on considering the reduction of residual strength in the design phase. However, in all the transport industry and particularly in the aerospace industry, the need for a lightweight and strong structure does not allow designers to overestimate the safety factor.
This work aims to develop and assess approaches to investigate how strain fields caused by loading conditions can be influenced significantly by the release of the stress state produced during the technological processes. In this regard, the interface damage of hybrid metallic/composite components and curved beam composite specimens are studied. In both cases, residual thermal stress plays a crucial role in the fracture and delamination behavior of the component.
In the first phase of the activity, the effect of residual thermal stresses on the fracture behavior of adhesive and matrix interfaces in the metal/composite hybrid specimens is investigated. The hybrid specimens studied in this work are enriched with optical fiber-based SHM systems to monitor the strain evolution during manufacturing and mechanical loading. Strain evolution during the curing cycle is used to calibrate a cooling simulation that evaluates residual stress prior to conducting the mechanical simulation. The resulting multistep numerical approach obtains an appreciable correlation with experimental forces, strain evolution, and final residual strain in the DCB tests. Experimental and numerical analyses indicate that residual thermal stress can affect the evolution of strains during crack propagation, the development of permanent displacements, and the forces required to propagate the cracks.
In the second part of the study, the effect of interaction between damage modes caused by complex stress states is investigated by the curved composite component. The activity was focused on validating and calibrating the numerical approach to developing a virtual tool for assessing the strength of the damaged component.

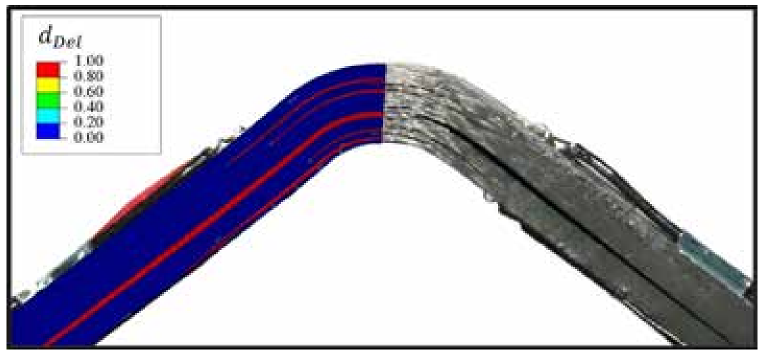

Fig. 1
Numerical/experimental correlation of damage behavior of Zero Specimen.

The numerical part is based on the constitutive law defined according to a bi-phasic approach developed in DAER to represent different damage modes of the fiber and matrix individually. The implementation of the method into finite element analysis has been illustrated. Two lamination sequences of [0]48 and [02/902]6s named as Zero and Cross-ply were selected to calibrate the law. Three specimens of each lamination were tested by a tensile loading application with the MTS machine. Zero specimens failed in the catastrophic failure of pure delamination with multiple interface damages. However, Cross-ply specimens experienced early failure caused by the interaction of damage modes.
The application of the bi-phasic numerical approach led to numerical results of the accurate prediction of damage scenario of both Zero (Fig.1) and Cross-ply (Fig.2) specimens compared to experimental results. In the case of Zero specimens, multiple delaminations similar to what Zero specimens experienced in the actual physical case were represented appreciably. Furthermore, two approaches were adopted for Cross-ply specimens to represent the in-plane damage, namely a method based on the CZM, which is well suited to model discrete transverse crack, and a method based on a progressive damage law, where matrix cracking is described through a diffused damage state.

The representation of residual stress state and introduction of Intra/Interlaminar damage interaction led to appreciable results using both approaches. Moreover, the approaches provided a good prediction of the damage evolution in pre-damaged elements, thus indicating the possibility to use the technique proposed to predict the residual strength of composite structural details.

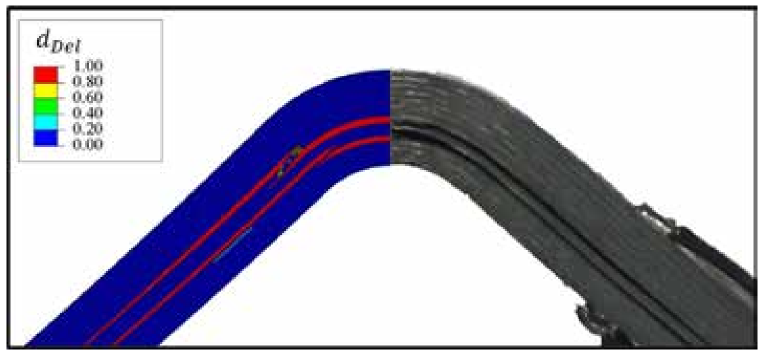

Fig. 2
Numerical/experimental correlation of damage behavior of Cross-ply Specimen.

SATELLITE INSPECTION OF UNKNOWN RESIDENT SPACE OBJECTS

Michele Maestrini - Supervisor: Prof. Pierluigi Di Lizia

In recent years, space debris has become a threat for satellites operating in Low Earth Orbit. Even by applying debris mitigation guidelines, their number will still increase in the next century. As a consequence, active debris removal missions, as well as On-Orbit Servicing missions, have gained momentum at both academic and industrial levels. The crucial step in both scenarios is the capability of performing an on-orbit initial study of the target resident space object: such task is commonly known as inspection. This task serves the purpose of collecting additional information on the target's condition, assessing damages, or even collecting information about it, should the target be an unknown object. To this day, inspection tasks have only been conducted in the neighborhood of known objects, either by autonomous chaser satellites or by humans (e.g. servicing missions of the Space Shuttle). However, with the increasing risk of new collisions and the generation of new debris owed to the situation in LEO, it is becoming increasingly important to be able to address the problem of inspecting an unknown object. The capability of performing this task autonomously may relieve the burden that is currently imposed on mission designers in order to tailor the inspection mission to the specific target under consideration. Most importantly, this task constitutes a completely overlooked field of research both from a Guidance as well as Navigation standpoint. Therefore, this thesis aims at providing a way of autonomously designing optimal trajectories in the neighborhood of an unknown target, while also building its dynamical and geometrical model by relying on an innovative navigation method. Conversely to standard proximity operations (i.e. rendezvous and docking), the inspection task requires optimizing the relative path between target and chaser in order to collect information rather than simply minimizing fuel consumption. Inspections are also a continued task that lacks a predetermined final condition or target state. Moreover, this problem is subject to many constraints, also operational ones. For these reasons, it is not only extremely difficult to design an optimal trajectory with classical optimization methods, but it is difficult to find a feasible solution in general. To tackle this problem this thesis relies on motion planning techniques, which constitute the state of the art in the field of autonomous robotics. The proposed method samples the possible maneuvers directly from the impulsive control action space and predicts the entire path in a receding-horizon-like approach. In doing so, it optimizes an inspection metric which is one of the contributions to state-of-the-art provided by this work. An example run of this algorithm is illustrated in Figure 1. Moreover, the input space is thoroughly searched for the best feasible action thanks to an innovative method based on subset simulation. The trajectory design relies on the capability of the chaser of retrieving a relative position and attitude estimate with respect to the target. Several techniques can deal with relative navigation at known and cooperative objects, fewer model-based methods are available if the investigated object is uncooperative (but known), while only a handful of techniques can deal with completely unknown objects. Indeed, this latter task requires building the target's map while navigating in its neighborhood. The approaches available to face this challenge have usually contrasting objectives and either provide an accurate reconstruction of the trajectory at the expense of the reconstruction of the target or vice versa. To overcome said limitations, this thesis also proposes a hybrid approach for relative navigation at an unknown and uncooperative target called COarse Model Based relative NAvigation. The main idea of this algorithm is to combine the advantages of different state-of-the-art approaches by splitting the mission into two phases. During the first phase, the navigation module focuses on reconstructing the geometrical model of the target as illustrated in Figure 2. In the second phase, this model is used as the base of a model-based relative navigation technique, effectively shifting the focus towards a more accurate trajectory prediction, as well as the characterization of the target from a dynamical standpoint. This work tries to leverage the structure of the particular model-based navigation method chosen so that measurement outliers can be detected and rejected automatically. To conclude, the applicability of this approach is evaluated on tumbling unknown targets whose period is retrieved from a database collecting real ground observations. In doing so, the thesis also evaluates the performance of the algorithm on space representative processor hardware whose outcome is summarized in Figure 3.

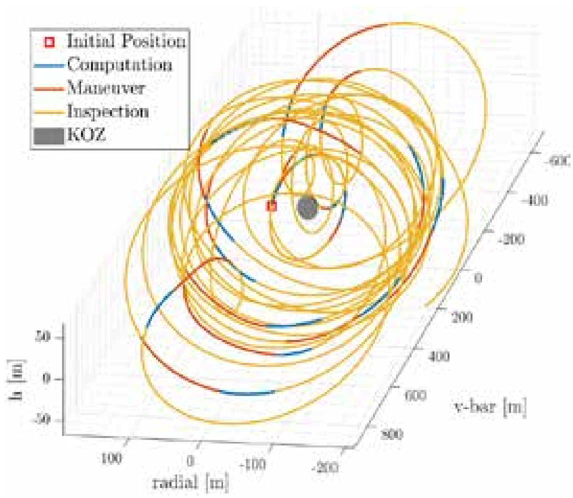

Fig. 1
Example relative trajectory for Inspection.

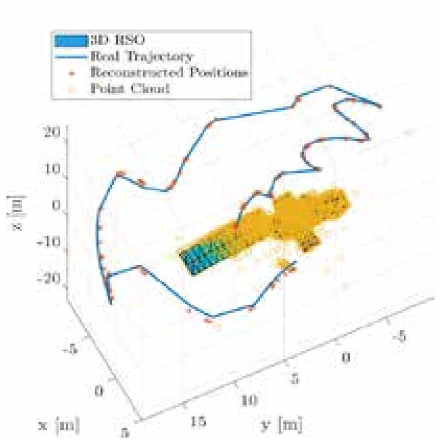

Fig. 2
Geometrical model reconstruction phase.

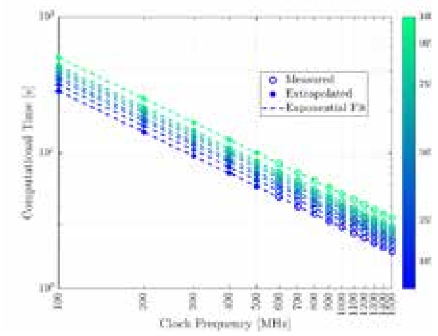

Fig. 3
Example runtime on ARM processor at different clock rates.

EXPERIMENTAL INVESTIGATION OF HELICOPTER-SHIP DYNAMIC INTERFACE

Neda Taymourtash - Supervisor: Prof. Giuseppe Quaranta

Shipboard operation is one of the most challenging tasks for rotorcraft pilots. In such an operation, due to the combination of moving flight deck, unsteady profile of the environmental wind and flying close to the hangar wall and superstructure of the ship, the velocity field over the deck becomes highly unsteady and turbulent which can negatively affect the performance and handling quality of the rotorcraft and may endanger the safety of the operation. Safety analysis for such demanding missions needs a series of at-sea trials which are inherently hazardous and extremely expensive. Consequently, development of the helicopter-ship Dynamic Interface (DI) simulation is considered a viable solution that reduces the cost and hazards of time-consuming at-sea test campaigns. Towards the development of a high-fidelity Dynamic Interface simulation, scaled experiments are proven to be beneficial and effective by providing reliable data collected from the controlled environment of the wind tunnel.

In this research, an experimental setup is developed to investigate the helicopter-ship Dynamic Interface, with the main focus on the aerodynamic interaction between the ship airwake and rotor inflow and its effect on the aerodynamic response of the rotor. Two wind tunnel test campaigns are carried out, each followed by a numerical simulation with the usage of experimental measurements to improve the prediction of aerodynamic loads obtained from a fully-coupled environment.

The test setup consists of a 1:12.5-scale model of Simple Frigate Shape 1 and a helicopter model, including the fuselage and a 4-bladed rotor. The first test campaign is divided into two main parts. In the first part, the topology of the flow field over the deck without the presence of the helicopter is investigated in three wind velocities, equivalent of 20, 35 and 50 knot in full scale, and three wind directions, including Headwind, Red15 and Red30. Pressure measurements and Particle Image Velocimetry on the flight deck are performed to characterize the main topology of the flow field over the deck and to understand the effect of the test parameters, namely wind velocity and direction, on the flow structure. Furthermore, Atmospheric Boundary Layer consistent with the coastal area is simulated, to consider the effect of a turbulent wind profile on the ship airwake. In the second part of the test campaign, the helicopter model is placed in a series of points, representative of a typical stern landing trajectory and a vertical descent above the landing spot. The rotor loads are measured at each point using a six-axis balance rigidly mounted inside the fuselage. Furthermore, in a selected number of points, the induced flow over the longitudinal symmetry axis of the rotor, while being immersed in the airwake of the ship, is visualized by means of Particle Image Velocimetry. Then, a nonlinear multi-body model of the experimental rotor is developed to identify a flow distortion element that reconstructs the variation of the rotor induced velocity due to the interaction with the ship airwake. This term is expected to reproduce the steady-state aerodynamic loads of the rotor while the helicopter is moving through the airwake of the ship. The second wind tunnel experiment aims to quantify the unsteady aerodynamic response of the rotor operating in various wind conditions and positions over the deck. This unsteady response reflects in handling qualities and workload of the pilot to maintain the attitude and position of the helicopter while performing a launch or recovery test. Consequently, correct modelling of the unsteady loads over the low-frequency bandwidth of interest is significantly important to obtain a more realistic level

of pilot workload in Dynamic Interface simulation. For the purpose of this test campaign, a new helicopter model is designed and manufactured which has a complete swashplate mechanism so that collective and cyclic commands can be applied to trim the aerodynamic loads. Taking advantage of the trim capability, the tests are performed in higher advance ratio with respect to the previous campaign. Furthermore, a "Dynamic Landing" manoeuvre is tested in which the helicopter is approaching the deck with a constant velocity, while the controls are applied to maintain the trim condition. Five wind conditions are selected, including Headwind with the velocity of 20 and 35 knot, Red30 with 20 and 25 knot and Red60 with 20 knot, all represented in full-scale values. After trimming the rotor loads at each test point, the time history of the aerodynamic loads is measured to be used for the unsteady assessment. Finally, the measured loads are employed to design the stochastic filters, based on the Autoregressive modelling technique, to reproduce the experimental spectra across the bandwidth of interest. Furthermore, one-way coupled simulation is performed by implementing the unsteady airwake of the isolated-ship, obtained from a time-accurate Computational Fluid Dynamics simulation, in the multibody simulation environment. Power Spectral Densities and unsteadiness of the aerodynamic loads obtained from the stochastic filters are compared with those from the experiment and simulation based on the one-way coupling approach.

AERO-SERVO-ELASTIC OPTIMIZATION IN CONCEPTUAL AND PRELIMINARY DESIGN

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Air transportation is a resilient and expanding market (+5% each year) and the aircraft fleet will increase by more than 20000 units in the next 20 years. Aircraft related CO2 emission share is 2% of the global ones, but the predictions suggest a strong increase in the next years. The interest towards climate changes urges the aircraft industry to design greener aircraft, following the prescriptions stated by different panels and committees (75% cut in CO2 by the 2050).

The exploitation of current technologies (New Engine Options, composite materials, flightpath optimization, ...) will reduce the emissions but they are not enough to invert the trend of growth and match the target. To obtain a significant reduction of the pollutants, breakthrough configurations and game changer technologies must be adopted.

The design areas that mostly affect the fuel consumption of the aircraft are the aerodynamics, the propulsion and the structures. It must be pointed out that few configuration changes can be done without incurring in multidisciplinary trade-offs, just as an example: increasing the wingspan to improve the aerodynamic efficiency lead to a structural weight increment.

The structural optimization dramatically reduces the weight of the aircraft, but slender and flexible structures are proner to aeroelastic instabilities, such as flutter. The fluid-structure-control system interaction, as known as aero-servo-elasticity, must be considered since the early design phases to avoid issues in the later development steps and add extra-costs and delays to the project.

The weight estimation in conceptual design phases is still based on statistical approach or company's legacy data; these methods are reliable for the classical aluminium wing-tube configurations, but they have a limited validity for new configurations (high aspect ratio wing, blended body, box-wing) and composite materials, due to low experience and poor statistical data availability. Moreover, aero-servo-elasticity is not accounted at this level.

For this reason, a physically based approach to the structural sizing and weight estimation was developed and named NeOPT, which is based on the existing aeroelastic analysis software NeoCASS. Its main features are:

- The increased fidelity of the wing-box description, obtained through a meta-model
- The possibility of developing active control laws for load reduction and stability augmentation
- The concurrent optimization of the wing structure and the active control systems.

The meta-model is an analytical three-dimensional representation of the wing-box, it collects geometrical information and structural properties (materials' characteristics and dimensions). This representation allows to expand the conventional stick model used in aeroelastic analysis into its analytical 3D description. The information stored in the meta-model can be re-arranged to generate and analyse different fidelity models like the global FEM of the wing-box, its stick-representation or a cross section FE model. The results can be exchanged between the analysis models: e.g. the internal forces distribution of a stick model is used to recover the stress state on the cross section or to generate an equivalent load case for the GFEM.

Moreover, it is possible to automatically generate a NURBS based CAD model of the wing-box.

The cross-section model is analysed with NeoANBA, a FE solver that provides the full 6x6 beam stiffness matrix and cross section stress distribution, accounting for the coupling terms introduced with orthotropic materials.

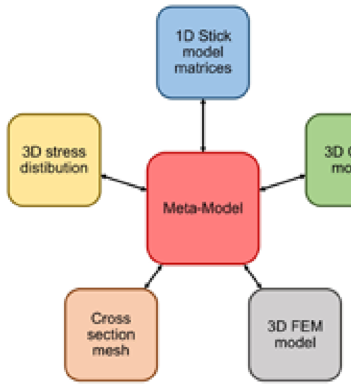

Fig. 1
Meta-Model pivotal role and available analysis models and results

This feature gives the possibility to consider aeroelastic tailoring with a simplified stick model. The meta-model increases the fidelity of the used beam model providing a more accurate evaluation of the stiffness properties and recovering the punctual stress distribution section wise.

Thanks to its analytical representation, whichever geometrical or properties modification of the wing-box is automatically mapped in all the analysis models without losing information and preserving the coherence among different representations of the same component.

Thanks to the NeoCASS capability of producing a State-Space model of the aero-elastic FEM+DLM model, a dedicated procedure for the auto-tuning of active control laws was developed. It consists in the minimization or maximization of a desired performance with respect to the open loop case, considering physical limitation for the control surfaces like deflection and deflection rate saturation, as well as actuator's bandwidth. Two separate wind tunnel models validated the control laws design methodology for Active Flutter Suppression (FAA founded program) and Gust Load Alleviation (Clean Sky 2 research program).

The improved wing-box description and automatic control law tuning were encompassed in an optimization framework that has as design variables the structural properties of the wing-box and as constraints its structural integrity (failure and buckling) and aero-elastic stability of the aircraft (no flutter). The objective function is the structural mass, but whichever analysis response can be used as objective or as a constraint, proving the flexibility of the tool. The analysis used for the constraints evaluation are all the ones available in a standard aeroelastic solver: trim, dynamic response and flutter solutions that can be simultaneously performed in a single optimization to consider multiple load cases and constraints.

An application of the NeOPT on a Twin-Aisle Long Haul aircraft shows how it is possible to evaluate the impact of increasing the wing span on the fuel burn and emissions, finding an optimal aspect ratio.

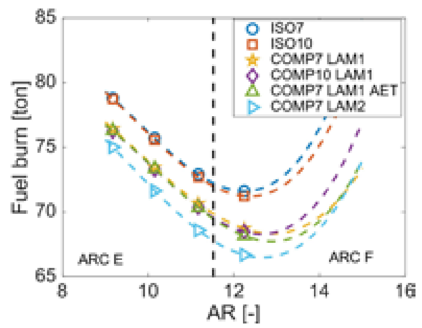

Fig. 2
Fuel burn on a 10000km mission for different structural solution and different Aspect Ratio

EFFICIENT INDIRECT OPTIMIZATION OF LOW-THRUST TRAJECTORIES WITH INTERIOR-POINT CONSTRAINTS

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Exploration and exploitation of the uncharted universe is an essential direction to push the scientific frontier, boom technological innovations and thrive the society. Ambitious space missions are envisioned to be implemented in the foreseeable future, involving expeditions to outer Solar System, human station construction on the Moon and Mars, asteroid mining, etc. The growing complexities of space missions, meanwhile the eternal pursuing of low-cost, high-risk and high-gain goals, pose a high requirement on the mission analysis and design.

In preliminary space mission phase, mission designers are interested in exploring and assessing as many trajectory options as possible, in a short duration and with limited resources. However, mission tasks related to low-thrust trajectory optimization are challenging that often require high computational load. For example, in asteroid missions, the trajectory designer has the task of filtering appropriate targets from thousands of asteroids, which involves assessment of tremendously high number of trajectories. However, numerical optimization methods are usually time consuming and their convergence is questionable. Thus, the efforts to enhance the rapid trajectory search capability with broader domains of convergence of the mission design tool are desirable. The low-thrust propulsion is the concern since it allows to deliver more payload to boost scientific return and it also allows missions with the velocity increment that are prohibitive with chemical propulsion. The success of a number of missions in recent decades, e.g., Deep Space 1, Hayabusa, SMART-1, and Dawn mission, has validated its reliability. This dissertation addresses the challenging low-thrust trajectory optimization problems. The goal is to improve the efficiency and effectiveness of the indirect method to advance and mature the mission design methods.

In trajectory optimization, the gradients of problem functions with respect to problem decision variables are at the heart of most methods. Finite difference methods are classical gradient estimation methods which approximate the gradients by truncating Taylor series of a function at a given point. Although these methods are straightforward and easy to implement, the computational load is usually high, and the accuracy inherently relies on the selected perturbation size, which is difficult to tune. Even though finite difference methods are sufficiently accurate in most cases, the gradient accuracy of finite difference methods is problematic for trajectory optimization with interior-point constraints, due to the discontinuity produced by interior-point constraints and bang-bang control. It is worth to exploit analytic gradients due to their high benefits on computational efficiency and gradient accuracy. This thesis successfully derived analytic gradients by using calculus of variations, calculated them through establishing the computational framework, and assessed their performance with comparison to the finite difference method, for low-thrust trajectory optimization with interior-point constraints.

Specifically, for low-thrust optimization with scalar interior-point constraints, analytical formulas of multipliers for both time-optimal and energy-to-fuel-optimal problems are obtained and leveraged such that the multi-point boundary value problem is solved as a two-point boundary value problem by using the developed methods. The state transition matrix for two categories of costate and dynamics discontinuities, produced by interior-point constraints and bang-bang control, respectively, are derived. The integration flowchart is further designed to involve interior-point event branches. Overall, the computational framework is established by combining analytic derivatives, continuation and switching detection into the augmented integration flowchart, which enables to achieve the desired discontinuous bang-bang solutions and their accurate gradients. The developed indirect methods have been applied to solve power-limited asteroid rendezvous and fuel-optimal many-revolution Earth-orbit transfers with eclipses. Moreover, the developed method has been used to solve thousands of time-optimal and fuel-optimal trajectories to favor asteroid screening in the M-ARGO (Miniaturised Asteroid Remote Geophysical Observer) mission. As a result, The list of 148 asteroids shapes the envelop of reachable targets by the M-ARGO CubeSat. Considering desirable mission parameters, the list is further reduced to 41 downselected objects, out of which 5 samples are extracted.

For low-thrust optimization with multi-dimensional interior-point constraints, the multi-dimensional multipliers have to be sought along with other unknowns. In this case, both state and costate may be discontinuous across interior-point time instants. Analytic gradients are derived for the deep-space transfer with intermediate flyby, rendezvous and gravity-assist events. The analysis is carried out for each segment first, then extends to the whole domain by using the chain rule. Special attention is paid to the derivatives of state, costate and constraints with respect to interior-point time instants, since the constraints considered are time-dependent. The recursive formulae of derivatives of each constraint with respect to unknowns at previous interior-point time instants are established. The fuel-optimal bang-bang solutions for deep-space transfers with intermediate flyby, rendezvous and gravity-assist events have been achieved. The main feature of our method is the capability to offer the desired fuel-optimal bang-bang solutions and their gradients. Numerical experiments show that the presented method enables to improve effectively the solver execution speed and enhance the optimizer robustness compared to the finite difference method.

Since the smoothing technique was introduced in low-thrust trajectory optimization, the homotopy continuation methods have been extensively developed in low-thrust trajectory design as an effective way to determine the solution with broader convergence domain. The homotopy method solves the objective problem by tracking the homotopy path, which is comprised of solutions of a series of auxiliary problems. However, it is observed that the continuation process has the potential to fail to proceed when the homotopy path encounters unfavorable conditions, such as limit points (where the Jacobian matrix is ill-conditioned) or the path goes off to infinity. In this aspect, pseudo-arclength method is a general method to effectively pass limit points by reversing the homotopy path direction and augmenting the Jacobian matrix. However, these methods may still fail, e.g., when the homotopy path grows indefinitely. This in turn calls for enhancements to improve the algorithmic robustness in homotopy methods.

This thesis designed tailored homotopy continuation methods for various low-thrust trajectory optimization problems. The combination of energy-to-fuel-optimal continuation and hyperbolic tangent smoothing is employed to expand the convergence domain for power-limited asteroid rendezvous trajectory optimization. Continuation strategies are designed to compute hundreds of asteroid pockchops in M-ARGO mission, in order to reduce the computational load, an effective continuation process is proposed to determine many-revolution, fuel-optimal transfers by gradually increasing the number of the shadow pass through. Additionally, the homotopy methods are designed to recover failures in homotopy continuation. The failure of thrust continuation for orbital transfers is resolved by connecting solutions with different revolutions. A generic homotopy method based on Theory of Functional Connections (TFC) is also developed. The TFC-based homotopy method implicitly defines infinite homotopy paths, allowing for the selection and switching of homotopy paths to remedy the failure of the continuation process.